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ABSTRACT

The feasibility of an intelligent venetian blind/lighting control system was tested in a 1:3 scale model outdoors under variable sun and sky conditions. The control algorithm, block direct sun and meet the design workplane illuminance level, was implemented using commercially available and custom designed blind and lighting systems hardware. While blocking direct sunlight, the blinds were properly controlled to maintain the design workplane illuminance within a tolerance of -10%, +25% when there was sufficient daylight. When daylight levels alone were inadequate, the electric lighting control system maintained the design workplane illuminance. The electric lighting could be turned off if a user-specified time period at minimum power was exceeded. Lighting energy savings of 51-71% (southwest) and 37-75% (south) was attained for the period from 8:00 to 17:00 on clear sunny days, compared to a fixed, partially closed blind with the same lighting system. Practical details for implementation and commissioning are discussed. The impact of control variations, such as profile angle, time step interval, and control area, on energy demand is investigated.

INTRODUCTION

Intelligent envelope and lighting systems in commercial buildings have significant opportunities for improving energy efficiency, moderating peak demand, and enhancing occupant comfort over and above that achieved by conventional, non-integrated design. While a more elegant realization of intelligent envelope and lighting control systems may have to wait for the development of thin film variable transmission glazings (e.g., electrochromic glazings), a reasonable level of intelligent control can be achieved with modifications, refinements, and ingenious combinations of available hardware components. For example, although not generally used for this type of control, motorized venetian blind systems are adaptable to specific envelope control strategies that maximize daylight availability and simultaneously keep solar gains to a minimum. This mode of operation is one of the more energy efficient strategies for harvesting daylight (Lee and Selkowitz 1995).

The objective of this research was to construct, using available hardware where possible, a working prototype of an integrated dynamic envelope and lighting system in order to investigate whether such a system could satisfy a specific set of performance criteria that address minimizing energy use while satisfying occupant comfort needs. A secondary purpose was to examine the implications of a dynamically-controlled integrated system with regards to the selection and specification of an appropriate supporting building controls infrastructure.

BACKGROUND

Manually operated internal venetian blinds are commonly used in commercial buildings to enable occupant control of the incoming daylight, view, and privacy on an individual room by room basis, although the frequency and reliability of their operation tends to be considerably less than energy-efficient (Inoue et al. 1988). There are several commercially available European and U.S. automated shading systems (venetian blinds and roller shades) that implement the simplest control strategy, block direct sun, but few are integrated with the lighting control system. In several high-rise office buildings in Tokyo, Inoue implemented control algorithms that raised and lowered a prototype venetian blind as well as tilted the blind angle to limit transmitted direct solar radiation and to maximize view. In other research, room luminance levels and brightness distributions detected by a charge-couple device (CCD) camera were used to control a motorized blind and electric lighting system (Glennie and Krishnamurthi 1991). A reduced-scale field test was conducted to ascertain lighting energy savings resulting from various venetian blind/ lighting control algorithms (Papamichael et al. 1986, Rubinstein et al. 1989), but the control system was not implemented in real-time.

METHOD

Performance Criteria

The performance objectives for the prototype system were:

1. The integrated blind/lighting control system shall provide a workplane illuminance design level of 538 lux (50 fc) within the range of -10% and +25%. Less tolerance was given for lower illuminance since this would likely be insufficient for office work.
2. The electric lighting system shall consist of commercially available, dimmable, electronically-ballasted fluorescent lamps.
3. The blind control system shall use a commercially available, motorized venetian blind mounted on the interior side of the window.[1]
4. The control system shall acquire data to assess performance and have user-adjustable "front panel" controls.
5. A minimum amount of custom control circuitry and computer software shall be utilized.
6. All control shall be derived from acquired sensor data and not rely on date and time information. Such reliance would increase the complexity of the commissioning process.

Scale Model

A single person, 3.3 m wide by 4.6 m deep (10x15 ft) office at 1:3 scale was instrumented and configured to test the automated venetian blind and lighting control system (Figure 1).

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[1] Thermally, between-pane venetian blind systems would be more energy-efficient; however, these systems were not tested here.

The 6.3 mm (0.25 inch) single pane clear glazed window was fitted with an interior motorized venetian blind. Electric lighting was modeled using full size fixtures and lamps.

Illuminance measurements were taken with Li-Cor 210S photometric sensors located in the center of each wall and the ceiling. Four sensors were positioned on the floor, centered from left to right of the window and located 1.2, 2.0, 2.7, and 3.3 m (full-scale) from the window wall. Global and diffuse horizontal exterior illuminance were measured using a Li-Cor photosensor with and without a shadow band apparatus.

The structure is located outdoors with a relatively unobstructed sky view on the roof of Building 90 at the Lawrence Berkeley National Laboratory, Berkeley, California. The window was oriented 34˚ west of true south and due south for consecutive tests.

Venetian Blind Hardware

Commercial motorized, interior horizontal venetian blinds were used for fenestration control (Levolor "Riviera"). The slightly curved, metal blind blades were 0.025 m (1 inch) wide with a matte/semi-specular, light pink surface. At full-scale, the venetian blinds were 0.46 m (1.5 ft) in height; as such, the same blind angle was easily achieved throughout the full height of the blind. Full-scale tests will more thoroughly test the precision of blind angle positioning for typical window heights of 1.8-2.1 m (6-8 ft).[2]

The electronic controls for the small direct current blind motor were not robust when subjected to frequent adjustment as would be typical with automatic operation. The controls for the motor were completely rebuilt by designing an electronic circuit that could accept digital control signals from the control system and translate these signals into appropriately scaled pulses to drive the blind motor to the desired position. Designing such a circuit for commercial use would not be a difficult task. Calibration of individual blinds during manufacturing will probably be required to determine the relationship between the control shaft position sensor's rotational position and the blind angle. Motor specifications should include sound dampening.

Blind fractional position, or tilt angle, was measured as the voltage divide in the potentiometer coupled to the blind control shaft. A value of 0.49 denotes a horizontal blind position. Values of 0.10 and 0.90 denote upward and downward fully closed positions, respectively. A value of 0.75, for example, denotes a more closed position with the blind blades tilted *downwards* so that an occupant has a view of the ground if the sight line follows the angle of the blade.

Electric Lighting Hardware

Fluorescent electric lighting was supplied by two three-lamp fixtures recessed into the false ceiling of the 1:3 scale model. Appropriately sized rectangular openings cut in the ceiling plane were designed to simulate two three-lamp 2x4 lensed fluorescent office fixtures. Prismatic panels (standard K12 pattern) were fit in the openings. Six 32 W T8 fluorescent lamps were installed in fixtures above these rectangular openings and were wired to three electronic dimmable ballasts. Lighting power was measured using a watt transducer (Ohio Semitronics GW5, accuracy: 0.2% of reading).

A complete, commercial lighting system was used initially. However, testing revealed the inadequacy of the components in meeting control objectives. The lighting system

[2] A full-scale testbed demonstration of this system is being conducted as of April 1996.

demonstrated inadequate feedback control of the fluorescent lighting. The fixed feedback gain of the ballast controller circuitry appeared to be insufficient to optimally reduce fluorescent light levels as workplane illuminance increased. The ballasts also appeared deficient; a minimum power reduction of 46% was attained where the manufacturer claimed 30%. Due to these encountered problems, the voltage output from the computer[3] was used to directly control a different type of dimmable ballasts (Motorola Helios™ M2-RN-T8-10C-120, 10% minimum light output, 33% minimum power) through a Honeywell EL7305 ballast controller. The lighting power shut-off capability built into the ballast controller was used. The new dimmable fluorescent ballasts were tested and found to perform per manufacturer's specifications; at the maximum dimming level of 11%, electrical power consumption was 31%.

Commercial ceiling sensors also proved to be inadequate. Several could not be adjusted to the desired light level of 538 lux (50 fc). Unshielded ceiling sensors were susceptible to extraneous light from the window plane. Modifications to the photosensor's lens could reduce the field of view and exclude extraneous light input. Shielded sensors proved unusable due to low sensitivity. Adjustments to some photometric amplifier circuits could make the sensors responsive at the light levels desired. Another sensor was found inadequate due to thermal drift. Improvements in offset drift could be realized with newer low bias current op-amp circuits that would not be prohibitively expensive.

A shielded Li-Cor ceiling sensor was tested whose signal showed good correlation to the average workplane illuminance. Shielding was accomplished by surrounding the input lens of the sensor with a matte black, painted aluminum circular tube. Its length was sufficient to prevent the sensor from seeing the blinds; the field of view was ~60˚. The signal did not appear to be significantly influenced by blind angle changes during the day, which indicated that the sensor's field of view was not excessively broad. As such, the shielded Li-Cor sensor was used for lighting and venetian blind control. A cheaper shielded Centronics photodiode replaced the Li-Cor in later tests (after 3/24/95).

Sun Angle Sensor

Satisfying the "block direct sun" control objective requires an accurate determination of the sun's altitude. This was accomplished with a sun angle sensor developed by LBNL which determines the sun altitude when the sun is in the plane of the window and whether direct sun is present. A real-time clock could accomplish the third objective, but would require commissioning at the job site to account for latitude and longitude as well as periodic maintenance. The sensor was designed to be robust under difficult site conditions; e.g., weather, tampering, etc. It is mounted on the exterior facade of a building and can serve numerous offices that share similar exterior window shading and view conditions. Real-time data from the exterior sensor must be routed to individual offices via low voltage wiring or other medium.

Sample data are given for winter and summer conditions in Figure 2. Under winter clear sky conditions (e.g., December 25), the day's average error of measurement was found to be within -1.3±1.2˚ when direct sun was present and in the plane of the window. Direct sun was present when the sun angle sensor signal was greater than ~1.0 V. The signal was typically at this strength when the ratio of global to diffuse horizontal exterior illuminance (E_g/E_{dif}) was greater than 1.2-1.5. Under variable conditions (e.g., January 17) when

3 The computer data acquisition/ control system is discussed in a later section.

direct solar is attenuated due to low daylight, hazy, foggy, or partly cloudy conditions, the average error of measurement was still acceptable for data points where $E_g/E_{dif}>1.5$: 0.9±1.8˚ from 10:00-16:00. The sensor's accuracy becomes less critical since strong direct sun is not present.

Summer data revealed that the sun angle sensor measured less accurately for solar altitudes greater than 45˚ (to within 10-17%). The sensor generally predicted a lower solar altitude. If this measured altitude is used for control, the venetian blind will be set to a more open position with increased daylight utilization. This was confirmed by monitored data (Table 2, July 30 South (actual solar altitude) and 31 (measured solar altitude)), where the summed lighting energy use from 9:19-17:00 was decreased by 11% than if controlled by the actual solar altitude. Later tests were conducted using the actual solar altitude (based on real-time) for control and are denoted in Table 2 with "$ß_{calc}$." Revisions to the sensor design are in progress.

Control Algorithm

National Instrument hardware and LabView software enabled graphically written control algorithms to be tested with a virtual instrument front panel, and facilitated monitoring and adjustment of the control system design. Commonly desired user adjustments for the venetian blinds included workplane illuminance minimum and maximum levels, frequency of blind readjustment, and trimming of blind position for greater slat openness or closure. Data inputs to the computer system, used to control the blinds, included the signal from the ceiling-mounted photosensor, electric lighting power consumption, sun altitude, and blind angle. Parameters such as workplane illuminance minimum level, deadband width, and lighting shutoff time delay were available for the lighting system.

The blind control system was designed to 1) block direct sun and 2) adjust the blind angle to maintain the design workplane illuminance with daylight, if sufficient daylight is available, and 3) maintain the total illuminance from the lights and daylight within the design illuminance range. If direct sun is not present, the computer control system sets the blind position to horizontal to maximize slat openness and the occupant's view of the outdoors. If direct sun is present, the control system calculates the correct blind angle that blocks direct sun, then adjusts the blinds.

The calibrated ceiling-mounted photosensor and lighting power consumption were used to determine if the blind adjustment met the illuminance control objective. If the illuminance level was outside the design workplane illuminance range, in this case I_{design}=485-675 lux (45-63 fc), the blinds were opened or closed until the illuminance was within range. When movement of the blinds was initiated, the blinds were moved in one direction only during that control loop to avoid unstable cycling of the blinds. The blinds were adjusted every minute to meet control objectives.

Fluorescent lighting was designed to supplement the daylight provided by the blind system. To reduce annoying on/off cycling of the lights (at 11% light output) during variable daylight conditions, the electric lighting was turned off only if the lighting was maintained at the minimum level for the user-specified number of minutes (in this case, 10 minutes).

Three correlations were required to determine the daylight and electric lighting contributions to the workplane illuminance level in the space, where the average of four workplane illuminance sensors, I_{avg}, was used as the benchmark:

A. Correlation between lighting power consumption (W) and I_{avg}, electric lighting only.

B. Correlation between ceiling-mounted sensor signal (V) to I_{avg}, electric lighting only.

C. Correlation between ceiling-mounted sensor signal (V) to I_{avg}, daylight only.

Correlation A: Lighting power to Iavg

The relationship between the input power to the ballasts and I_{avg} over the entire electric lighting dimming range for two different test day conditions is given in Figure 3. The relationship was measured by covering the window with an opaque surface to exclude daylight and manually setting the dimming levels. For the same power input, there was some variation in lighting system efficiency due to differences in ambient air and lamp temperature. The correlation shown represents a conservative position, where the least efficient lighting output is assumed. In the region of minimum power, a step function was used to approximate the typically ill-defined relationship of wattage to light output. From 40-57 W, the illuminance output was set at 95 lux (9 fc). For input power levels less than 40 W, the illuminance was set to 0 lux.

While power consumption data are typically not available in commercial lighting control systems, the relative output of the electric lighting can be obtained using the control voltage applied to the ballasts. However, this solution may be more sensitive to environmental and lighting component changes and may require more frequent recommissioning. The solution to this problem will be addressed in future work.

Correlation B: Ceiling Sensor to Electric Light

The correlation between the ceiling-mounted photosensor signal (V) and I_{avg} over the entire dimming range is given in Figure 4. The illuminance levels differed significantly between March 27 (14:57-15:18) and April 4 (18:00-18:23) due to changes in lighting system efficiency – the ambient air temperature varied considerably since the outdoor scale model was not space conditioned. A stable thermal environment is typical for commercial applications. The final correlation was obtained by making custom adjustments to ensure conservative lighting control and to reconcile the differences in the ceiling-mounted sensor's spatial and spectral response to daylight and electric lighting.

The electric lighting correlations A and B may change if the space is substantially altered (e.g., furniture, paint or carpet color). Recommissioning of the lighting system will be required to ensure proper control. Diminishment of light output due to aging lamps, or lumen depreciation, is accounted for in this closed-loop system.

Correlation C: Ceiling Sensor to Daylight

The correlation between the ceiling-mounted photosensor signal (V) and I_{avg} is potentially complicated by the venetian blind system. To what degree is this correlation affected by the daylight spatial distribution resulting from this semi-specular blind? Will the correlation change for different seasons or window orientations? Such dependencies will determine whether the system will be easily commissionable and modifiable.

This relationship was determined on a sunny day, December 29, for the Li-Cor ceiling-mounted photosensor and southwest orientation. The blind fractional position (i.e., slat angle) was varied throughout the day with the electric lighting system off. The correlation was weighted toward sunny conditions; hence, data for the early morning hours when the sun was out of the plane of the window were not included. Significant deviations when one of the workplane illuminance sensors was struck directly by a spot of sunlight coming through the string hole in the blind blade were also not included.

The correlation was checked on a synthesized[4] partly cloudy day, January 13-16, and two partly cloudy days, January 17 and 18 (Figure 5). With daylight only, the measured I_{avg} was maintained within the specified I_{design} range by the correct position of the blinds, when sufficient daylight was available and when sunlight spot glitches were not detected. This confirmed that the daylight optimization control objective was being met with the blind system for most hours. When there was a deviation between the measured I_{avg} and the ceiling-mounted photosensor's calibrated workplane illuminance, I_{calib}, a significant contributing factor was the non-uniform asymptotic spatial distribution of daylight, typical of sidelighting. During sunny conditions, the daylight levels nearest the window tend to drive up I_{avg} erroneously. The difference between I_{avg} and I_{calib} is plotted against the ratio of the measured workplane illuminance at 1.2 m (I_a) to the illuminance at 2.0 m (I_b) from the window wall for January 13-16 (Figure 6). I_{calib} increasingly deviates from I_{avg} as the front workplane sensor reading increasingly deviates from the adjacent workplane sensor ($I_a/I_b \neq 1$). Average differences in illuminance are given for incremental categories of I_a/I_b in Table 1. Note that the correlation again leads to a conservative estimate of daylight illuminance; the actual illuminance, I_{avg}, is typically greater than the predicted, I_{calib}. When there was sufficiently uniform daylight distribution ($I_a/I_b \approx 1$), there remains a spread of data points, an indication of the correlation's slight dependency on blind fractional position.

Similar correlations were made for the Centronics ceiling-mounted photosensor in March 1995 (Figure 7), then used for various tests throughout the summer and early winter. Unfortunately, the Centronics voltage data were not recorded for these tests, so independent evaluation of the correlation as environmental conditions change (summer/winter, south, west, southwest) was not possible. Previous research (Rubinstein et al. 1989) monitored this relationship in this same LBNL field test facility for various orientations throughout the year, and concluded for shielded photosensors that the correlation slope did not change significantly between seasons or with blind angle; hence, calibration need only be performed once.

Since all three correlations were used to determine the optimal position of the blinds, errors introduced by each correlation have a compound effect. The electric lighting correlations were therefore tuned to conservatively underestimate the contribution of electric light to the workplane. The daylight correlation tended to also underestimate its actual contribution. The result is a more conservative positioning of the blinds (more open) with less energy savings than could probably have been attained.

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[4] Unusually stormy weather was experienced throughout this California winter; hence, "synthesized days" were compiled by concatenating data for clear sky conditions (E_g/E_{dif}>1.5) from various partly cloudy days.

PERFORMANCE EVALUATION

Control System Performance

An example of typical blind and electric lighting control system operation is given for a sunny day, February 18, 1995 Southwest (Figure 8).[5] For daytime hours, the control system was able to maintain I_{avg} throughout the day with daylight and electric light to within 571±56 lux, excluding the few erroneous short period glitches caused by the blind blade holes that admit sunlight spots on the workplane. Periods when I_{avg} exceeded the I_{design} range occurred at ~9:15 and 13:45. These are likely caused by atmospheric haze and fog which increased the illuminance level at the front sensor.

The dimmable fluorescent lighting was well integrated with the blind control system. Electric lighting smoothly supplemented daylight during early morning and late afternoon hours while maintaining I_{design}. Response of the lighting system to available daylight was adequate. From 10:25 to 16:35 (6 hours) on this winter day and southwest orientation, no fluorescent lighting was necessary and was shut off after an initial delay period of 10 minutes.

Other winter and summer sunny days for the south and southwest orientations were found to perform satisfactorily within control specifications (Table 2: Control Performance). I_{avg} was maintained within the I_{design} range of 485-675 lux (45-63 fc) given control by calculated altitude, $ß_{calc}$. Generally, the measured workplane illuminance, I_{avg}, tended to be 4-6% higher than the predicted illuminance, I_{calib}, ensuring conservative control.

There are theoretically two cutoff blind angles that block direct sun (Figure 9). When the sun comes into the plane of the window, the blinds can be initiated from horizontal (maximize view) to either of two cutoff angles. For all solar positions, the more open and upwards[6] position will yield higher interior illuminance since it "sees" the brighter sky. To avoid blind oscillations and "hunting" as the control system satisfies the control objective – optimize daylight admission – the initiated direction is reversed only when a boundary condition is reached. As such, subsequent blind angles are determined by the direction first initiated to block direct sun. Since the relationship of daylight illuminance to blind angle is non-linear (Figure 10) and movement is restricted, control optimization is made more complex.

This is exemplified on a sunny summer day, August 3, where the blinds were first initiated in an upwards position at 10:30 to block direct sun when the sun comes into the plane of the southwest window (Figure 11). Selection of this angle yields the highest level of daylight, ~350 lux (32 fc), of all possible blind angles, and therefore satisfies the "optimize workplane illuminance" criteria. Daylight is insufficient to meet I_{design}, so some electric lighting is provided. From 10:30-12:15, the blind continues to be adjusted in an increasingly upwards position in order to just block the rising sun while the workplane illuminance is allowed to increase until it reaches the I_{design} upper boundary (675 lux). Electric lighting is reduced until ~12:00 when it can be shut off. At 12:15, a reversal of direction is necessary when the upper I_{design} limit is reached, and a large motion in the blind results to sufficiently attenuate incoming daylight; i.e., a ~45° angle change within a

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5 Data given for the Li-Cor ceiling-mounted sensor configuration.

6 "Upwards" and "downwards" movement of the blinds denotes the pivoting angle of the blind blade around a horizontal axis, where the upwards direction permits the occupant to see a view of the sky. "Open" and "closed" denotes the amount of space between individual blind blades.

one minute interval. Less movement of the blinds (and more view) is possible by selection of a more horizontal blind angle that also blocks direct sun; however, the daylight illuminance control objective may not be optimally met from 10:30-12:15.

While this control example results in satisfaction of all control objectives, lighting quality and visual comfort may not be optimal. There is a 4:1 gradient of light from the front to the back of the room and an occupant may be able to see a direct view of the sky since the blinds are positioned upwards. Again, a more horizontal blind angle will increase daylight uniformity throughout the space, but will lessen energy savings.

Partly cloudy conditions result in large perturbations in exterior illuminance levels and so must be accommodated carefully in the control system to avoid unnecessary oscillations of the blind. This behavior was noted in the February 18th example above, where atmospheric haze and fog confounds the system in early morning hours, ~9:15. While not implemented in these tests, a time delay should be imposed on the system if a "large" change is noted; e.g., the blind can be set to block direct sun but not optimize workplane illuminance for a five to ten minute duration, then moved a small increment to account for changing sun angles.

Demand and Energy Savings

Tests on near consecutive days were made to determine the electric lighting power savings achieved by the dynamic blind system over a static blind system with the same electric lighting system (Figure 12). Cooling energy reductions were investigated in a separate study (Lee et al. 1994, Klems et al. 1994). Clear sky days with similar solar data between the fixed and dynamic tests were used to ensure an equitable comparison. The "fixed" blinds case set the blade angle to just block direct sun for the near lowest solar altitude (~5˚) expected during most of the day (tilted downwards ~70˚ from horizontal, where 90˚ is closed). From late afternoon to sunset, the blinds were then adjusted every minute to block direct sun (assuming active intervention by the occupant[7]). During some short early morning and late afternoon periods, this position may allow in some direct sun.

When compared to the fixed blind, all active configurations of the control system required substantially less lighting energy to maintain workplane illuminance levels. The active blind decreased lighting demand and energy use by 37-75% for south-facing windows and by 51-71% for southwest-facing windows compared to the fixed blind.[8] Data are summarized in Table 2: Lighting Demand and Energy.

With this control algorithm, the electric lighting was turned off after a delay of 10 minutes if I_{design} was met by daylight. However, some occupants like the lights "on" as a tacit sign of occupancy. Demand savings would be less if the lights are dimmed to 31% power consumption at 10% light output without the shut-off option. The active blind would decrease average lighting demand by 21-26% if south-oriented and 20-26% if southwest-oriented compared to the fixed blind.

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7 Studies have shown that manual operation of the blind is fairly unpredictable. Often, the occupant is not in the office for a significant part of the day. (Inoue et al. 1988, Elrod et al. 1993)

8 The following dates denote comparable fixed and active blind tests, respectively: Southwest: 6/25 (fixed) & 7/6 (active); 9/12 & 9/18; South: 6/24 & 6/22; 7/27 & 7/30; 9/7 & 8/19; 10/13 & 10/1. Data can be found in Table 2.

If no daylighting controls are used, the baseline demand would be 120 W to yield an I_{avg} of 538 lux (50 fc). The active blind would decrease average lighting demand by 62-83% compared to this no daylighting controls baseline if south-oriented, and 69-79% if southwest-oriented. If no shading is used throughout the day, data from previous tests (Klems et al. 1994) showed that early over saturation of daylight resulted in nearly the same lighting power reduction as the automated blind, but window heat gains were significantly higher during winter hours for a southwest oriented window.

Profile Angle

Other control algorithm variables were investigated to determine their effect on energy performance. The use of the sun altitude versus profile angle to block direct sun is one such variable. The profile angle[9] accurately depicts the position of the sun in relation to the horizontal blind plane since it incorporates the surface solar azimuth angle.[10] The difference between the profile and altitude angles is acute when the surface solar azimuth angle is high. If hardware (versus calculation) is used to determine the position of the sun, additional sensor complexity and cost would be required to determine this angle. And while the profile angle is more accurate, the altitude angle results in a more conservative blockage of direct sun.

For *south*-facing windows, daylight utilization should be nearly the same for winter solar conditions since the difference throughout the day between the two angles is small, roughly 4-5°. For summer conditions, the profile angle is significantly higher than the altitude angle during early morning/ late afternoon hours – ~36° on June 21 at 9:00 – which results in poorer daylight utilization since the blind would be positioned at a more acute upwards and *closed* position than if the altitude angle was used. For mid-day hours, there is an insignificant difference between these angles. Summer monitored electric demand with profile angle control was increased by 10% (poorer daylight utilization) than if controlled by altitude (Table 2).

For *southwest*-facing windows and winter conditions, the profile angle is higher during winter morning hours – ~62° on December 21 at 8:00 – but due to the lower sun angle, the blind is set to a more upwards and *open* position than if the altitude angle was used. Using extrapolated December 29 data, daylight utilization was estimated to be ~7% higher with the profile angle from 9:00-17:00, where I_{design} was reached ~45 minutes earlier in morning hours. In summer, the differences in these angles occur in the late afternoon to evening – 29˚ higher on June 21 at 18:00 – daylight utilization should be better with the use of the profile angle. Monitored lighting demand (August) using the profile angle for control was decreased by 7% than if controlled by altitude.

In summary, the use of profile angle for blind control increases daylight utilization for the southwest orientation during morning to mid-day hours throughout the year and decreases daylight utilization for the south during early/ late summer hours. For sites which have low daylight availability due to weather, exterior obstructions, or a low effective window aperture, the use of the profile angle for control may be worthy of further investigation.

Control Area

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9 Profile angle, Ω, is the angle between the surface outward normal of the window and the rays of the sun projected into the plane perpendicular to the window plane.

10 The surface solar azimuth angle, γ, is the angle between a line normal to the vertical glazing surface and the solar azimuth angle.

The control system correlations were based on the average workplane illuminance throughout the depth of the room. On clear sunny days, the strong asymmetric distribution of daylight causes the frontmost photometer to read significantly higher than the other three photometers. This in turn makes the average illuminance calculated from these photometers to be more indicative of the illumination at the front of the space rather than across the depth of the entire space, as intended. In terms of control, this "misaveraging" causes the control system (both in terms of blade position and electric light level) to "starve" the back half of the room of light. In typical commercial installations, this problem could be avoided by 1) making sure that the ceiling-mounted control photosensor is located towards the rear of the room (two-thirds of the room depth represents a good compromise) and 2) using only one location at the workplane per control zone for commissioning the control system (rather than averaging across the space as we have done). For this test, if we examine the individual workplane illuminance levels at the back of the room, we find that the levels nearly meet the design target for the majority of the day, as shown in Figures 13 and 14 for typical winter and summer clear sunny days. For February 18th, the workplane illuminance at 2.7 m (9 ft) from the window wall was closely maintained within the I_{design} range of 485-675 lux: I_c=457±39 lux (42±4 fc) from 8:00-17:00; and for August 3, I_c=433±41 lux (40±4 fc).

If the blind and lighting system had been controlled based on the illuminance at the back of the room, this control variation would have resulted in more blind openness, increased daylight at the front of the room (with potential visual discomfort), and less overall lighting energy savings given the same I_{design} since daylight availability is lower in the back of the room. This method of control will be used in future tests.

Frequency of Blind Activation

Less frequent activation of the blind will increase the longevity of the motorized system, diminish the attention drawn to it by the occupant (who may dismantle or override the system if found annoying), and dampen blind oscillations in partly cloudy conditions.[11] If the time step is lengthened, the control system may not fully meet control objectives; e.g., optimize workplane illuminance. Extrapolation of the monitored data showed that there would be a ~1-2% increase in lighting demand if the time step was increased from one to five minutes for south and southwest orientations throughout the year (Table 2). As an alternative, the time step may be varied as the solar altitude's rate of change increases or decreases over the course of the day or year.

Blind Angle Range

The full range of blind angles was permitted for this test. Limiting the range to the downwards positions may result in increased visual comfort and a diminishment of direct source glare since the view of the sky will always be obstructed. This will limit daylight utilization. Tests at full-scale can determine if this is a critical issue. The absence of an unobstructed view may also be of concern. Most U.S. motorized systems do not allow for full retraction of the blind; higher end applications could allow for this control option.

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[11] These control issues are being studied in a full-scale test facility, as of April 1996. Subjective surveys will also be conducted to determine user acceptability and preferences of this automated system.

CONCLUSIONS

An integrated venetian blind and lighting control system was successfully designed to maintain the desired workplane illuminance in a 1:3 scale model single person office space under a wide range of sun and sky conditions. While blocking direct sunlight, motorized venetian blinds were properly controlled to maintain a design workplane illuminance of 538 lux within a tolerance of -10%, +25% when there was sufficient daylight. When daylight was insufficient, a continuous dimming electric lighting system added supplementary lighting which properly met workplane illuminance control objectives.

Electric lighting energy use and demand savings were significant. Coupled with cooling energy savings resulting from control of solar gains, the dynamic blind/ lighting system offers excellent energy savings potential as well as the ability to manage thermal and visual comfort. If the electric lights are allowed to be shut off after a 10 minute delay when there is sufficient daylight to meet the design workplane illuminance level, one can attain a lighting energy savings of 37-75% for a south to south-west facing window on clear sunny days, compared to a partially closed fixed blind with a comparable lighting control system. If the lights do not have a shut-off option, the savings are less: 20-26% compared to the fixed blind. If the baseline has no daylighting controls, the active blind can attain lighting savings of 62-83%. Increasing the interval of blind activation from 1 minute to 5 minutes decreased lighting savings 1-2%. Use of the profile angle for blind control could increase lighting savings if used at appropriate times of the day. Use of a control area weighted towards the back of the room will reduce energy savings.

Implementation of the system using commercially available components is possible with some minor modifications. More work is required to ensure that a simple commissioning process can be completed at the job site with reliable control. Additional work is currently in progress to address occupant-based control criteria (e.g., frequency of blind activation, lighting quality) in a full-scale testbed facility.

ACKNOWLEDGMENTS

The authors are indebted to the Pacific Gas and Electric Company, Department of Research and Development, San Ramon, CA for the use of their computer system, and to Levolor, Honeywell, and Advance for donated equipment. Thanks are also in order to graduate students, Christopher Pawlowski, Andrew Hamilton, and Paul Fritz.

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TABLE 1
ILLUMINANCE DATA FOR 8:00-17:00, DAYLIGHT ONLY

Date		If Ia/Ib<1 then Iavg-Icalib (lux)	1<=Ia/Ib<2 Iavg-Icalib (lux)	2<=Ia/Ib<3 Iavg-Icalib (lux)	3<=Ia/Ib<4 Iavg-Icalib (lux)	Ia/Ib>=4 Iavg-Icalib (lux)
1/13/95	Avg.	321	-17	58	240	909
-1/16/95	S.D.	231	38	50	0	620
	Max.	664	106	113	240	2,011
	Min.	98	-119	-13	240	215
1/17/95	Avg.	357	-24	54	no data	122
	S.D.	275	30	30	–	0
	Max.	785	67	88	–	122
	Min.	97	-89	14	–	122
1/18/95	Avg.	144	-32	70	201	825
	S.D.	102	22	0	0	268
	Max.	238	49	70	201	1,161
	Min.	50	-86	70	201	469

Notes:
Blinds controlled by measured solar altitude. Shielded Li-Cor used for this southwest orientation.

Eg	Global exterior horizontal illuminance (lux).
Edif	Diffuse exterior horizontal illuminance (lux).
Eg/Edif	If this ratio exceeds 1.5, direct sun is present. If it is lower, partly cloudy conditions exist.
Icalib	Calibrated workplane illuminance (lux) as determined by the ceiling-mounted photosensor signal and correlation shown in Figure 5.
Iavg	Average measured workplane illuminance (lux).
Ia	Measured workplane illuminance (lux) at 1.2 m from the window wall.
Ib	Measured workplane illuminance (lux) at 2.0 m from the window wall.
Avg.	Average
S.D.	Standard Deviation
Max.	Maximum
Min.	Minimum

TABLE 2
MEASURED LIGHTING ENERGY USE AND WORKPLANE ILLUMINANCE
SOUTHWEST

				Control Performance:			Lighting Demand and Energy:				
Control	Date	Sky		Icalib (lux)	Iavg (lux)	ΔI (lux)	1-min (W)	5-min (W)	30%P (W)	ΔL (%)	Total (Wh)
SW Bmeas	5/28/95	Sun	Avg.	525.4	578.0	26.1	30.0	30.1	61.1	75%	270
			S.D	44.3	53.3	30.8	35.0	35.1	13.3		
SW Bmeas	7/6/95	Sun	Avg.	526.6	562.1	16.0	40.4	41.1	66.2	66%	365
			S.D	37.1	42.2	13.1	37.7	37.7	12.4		
SW Bcalc	7/12/95	Ptly	Avg.	527.6	575.5	25.8	34.7	34.7	64.1	71%	313
		Cloudy	S.D	40.3	38.7	26.9	38.2	38.4	15.5		
SW Bcalc	8/3/95	Sun	Avg.	530.4	567.0	14.3	33.2	33.7	63.4	72%	300
			S.D	39.4	36.9	15.4	36.9	37.1	13.4		
SW Bcalc	8/5/95	Ptly	Avg.	528.8	591.8	40.3	34.9	36.0	65.7	71%	315
		Cloudy	S.D	39.7	46.6	43.6	39.9	40.2	16.2		
SW Bcalc	8/8/95	Sun	Avg.	529.6	563.5	13.5	36.7	37.0	65.8	69%	331
			S.D	39.2	34.9	12.9	38.5	38.6	13.0		
SW Bcalc	9/18/95	Sun	Avg.	540.0	561.2	-4.5	24.9	25.3	62.5	79%	224
			S.D	43.2	71.5	33.1	36.5	36.8	14.0		
SW Prof	7/14/95	Sun	Avg.	526.7	566.4	22.5	39.5	39.8	69.3	67%	356
			S.D	38.6	57.8	42.3	42.1	42.3	15.4		
SW Prof	8/9/95	Sun	Avg.	532.5	559.5	5.3	34.0	34.0	67.1	72%	307
			S.D	40.8	53.9	28.0	41.4	41.5	16.2		
SW Fixed	6/25/95	Sun	Avg.	503.5	482.0	-23.9	83.0	83.0	83.0	31%	748
			S.D	6.8	16.1	15.0	10.3	10.3	10.3		
SW Fixed	9/12/95	Sun	Avg.	503.2	472.7	-32.2	84.3	84.4	84.3	30%	760
			S.D	5.6	25.6	25.0	18.3	18.4	18.3		

Notes: All data given for Centronics sensor.
SW=Southwest, S=South, Bmeas=Measured Sun Altitude, Bcalc=Calculated Sun Altitude, Prof=Profile Angle, Fixed=Fixed Blind, Ptly=Partly, Avg=Average, S.D.=Standard Deviation,
Icalib: Calibrated workplane illuminance from daylight and electric light for Eg/Edif>1.5 for 8:00-17:00.
Iavg: Average measured workplane illuminance from daylight & electric light for Eg/Edif>1.5 for 8-17:00.
ΔI: Average of Icalib–Iavg for 8:00-17:00 when Ia/Ib<4 (light uniformity) and Eg/Edif>1.5 (direct sun).
1-min, 5-min, 30%P (W): Average lighting demand if blind activated at 1-minute or 5-min intervals or if the minimum lighting power is 30% (instead of lights off at 0% power after time delay of 10 minutes).
ΔL: % Difference in lighting demand between 1-min blind system and no daylighting controls (120 W).
Total: Summed energy use (Wh) from 8:00-17:00 (1-min blind), unless otherwise noted.

TABLE 2
MEASURED LIGHTING ENERGY USE AND WORKPLANE ILLUMINANCE
SOUTH

	Control	Date	Sky		Control Performance: Icalib (lux)	Iavg (lux)	ΔI (lux)	Lighting Demand and Energy: 1-min (W)	5-min (W)	30%P (W)	ΔL (%)	Total (Wh)
S	Bmeas	6/22/95	Sun	Avg.	503.3	547.4	33.7	56.3	56.7	66.0	53%	508
				S.D	25.0	43.8	16.9	27.7	27.6	11.6		
S	Bmeas	7/31/95	Sun	Avg.	528.5	554.7	12.5	35.3	35.8	62.2	71%	272 a
				S.D	41.4	46.4	17.7	34.6	34.6	10.5		
S	Bcalc	7/18/95	Ptly	Avg.	526.6	600.5	52.6	25.7	26.1	61.2	79%	232
			Cloudy	S.D	37.1	73.5	53.1	33.9	34.2	10.2		
S	Bcalc	7/30/95	Sun	Avg.	520.9	556.3	18.9	45.7	46.2	65.7	62%	412
				S.D	35.2	40.4	9.5	34.9	35.0	11.8		304 b
S	Bcalc	8/19/95	Sun	Avg.	527.4	552.1	3.5	32.1	32.4	63.9	73%	290
				S.D	39.3	47.8	11.5	37.2	37.5	12.4		
S	Bcalc	10/1/95	Sun	Avg.	557.2	550.6	-6.7	20.1	20.1	62.6	83%	168 c
				S.D	38.5	50.2	24.9	36.4	36.5	15.7		
S	Bcalc	11/8/95	Sun	Avg.	532.7	558.4	-5.9	32.6	32.9	65.8	73%	294
				S.D	41.8	105.4	43.0	40.6	41.0	16.8		
S	Prof	7/15/95	Sun	Avg.	516.0	541.3	13.3	56.5	56.8	74.9	53%	509
				S.D	31.8	94.3	69.2	41.8	41.9	19.6		
S	Prof	7/26/95	Sun	Avg.	518.6	531.6	-1.8	50.4	50.9	72.3	58%	454
				S.D	34.6	81.6	62.1	42.1	42.1	18.5		
S	Prof	11/14/95	Sun	Avg.	494.8	550.5	-16.0	19.0	19.3	62.5	84%	171
				S.D	97.1	87.9	35.1	35.6	36.0	14.4		
S	Fixed	6/24/95	Sun	Avg.	501.1	483.0	-19.5	89.1	89.1	89.1	26%	803
				S.D	6.6	15.4	13.6	7.3	7.4	7.3		
S	Fixed	7/27/95	Sun	Avg.	497.7	483.6	-15.5	90.8	90.8	90.8	24%	685 d
				S.D	6.7	9.9	9.8	5.8	5.8	5.8		
S	Fixed	9/7/95	Sun	Avg.	501.6	470.2	-31.4	80.7	80.8	80.7	33%	727
				S.D	6.6	18.2	18.7	11.7	11.9	11.7		
S	Fixed	10/13/95	Sun	Avg.	509.9	478.2	-35.9	80.1	80.2	80.1	33%	682 e
				S.D	6.9	50.0	22.5	13.4	13.5	13.4		

Notes: a) Total lighting energy for 9:19-17:00; b) 9:28-17:00 and 9:19-17:00; c) 8:38-17:00; d) 9:28-17:00; e) 8:30-17:00.

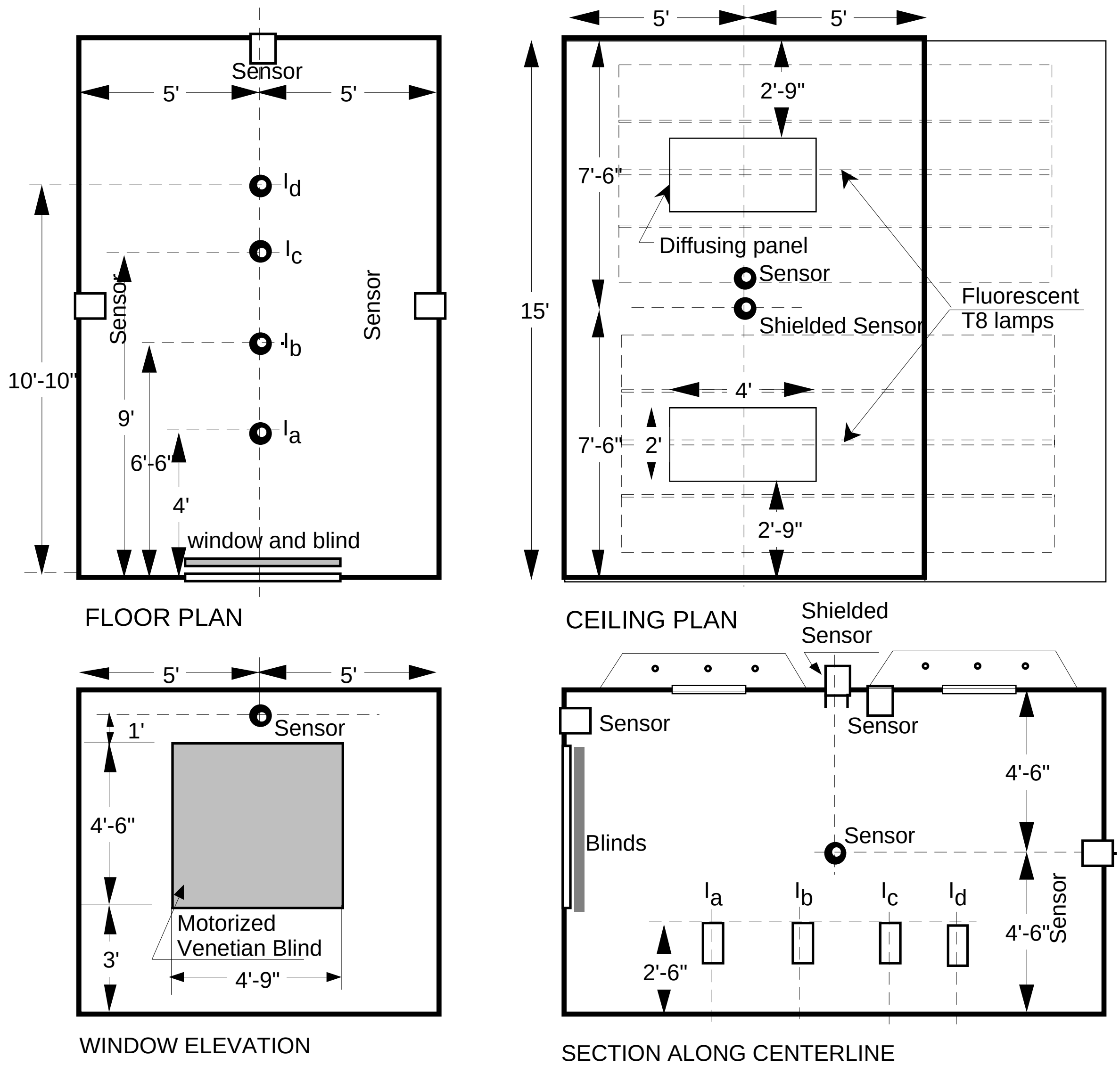

Figure 1. Plan and section of 1:3 reduced-scale model. Dimensions are shown in full-scale.

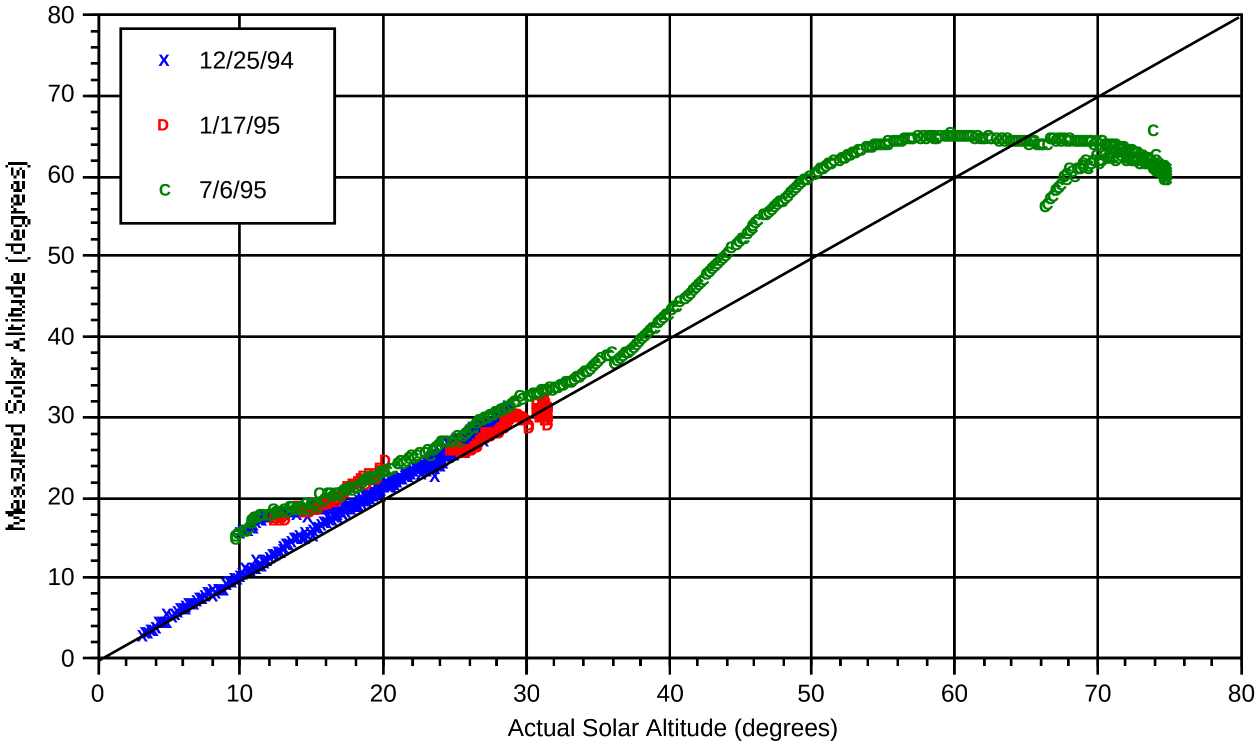

Figure 2. Measured versus actual solar altitude for a clear sunny day, December 25 (8:30-16:40), a partly cloudy day, January 17 (10:00-16:00), and a clear sunny day, July 6 (10:45-18:30), for a southwest facing window. Data are shown for periods when direct sun was detected (E_g/E_{dif}>1.5) and in the plane of the window.

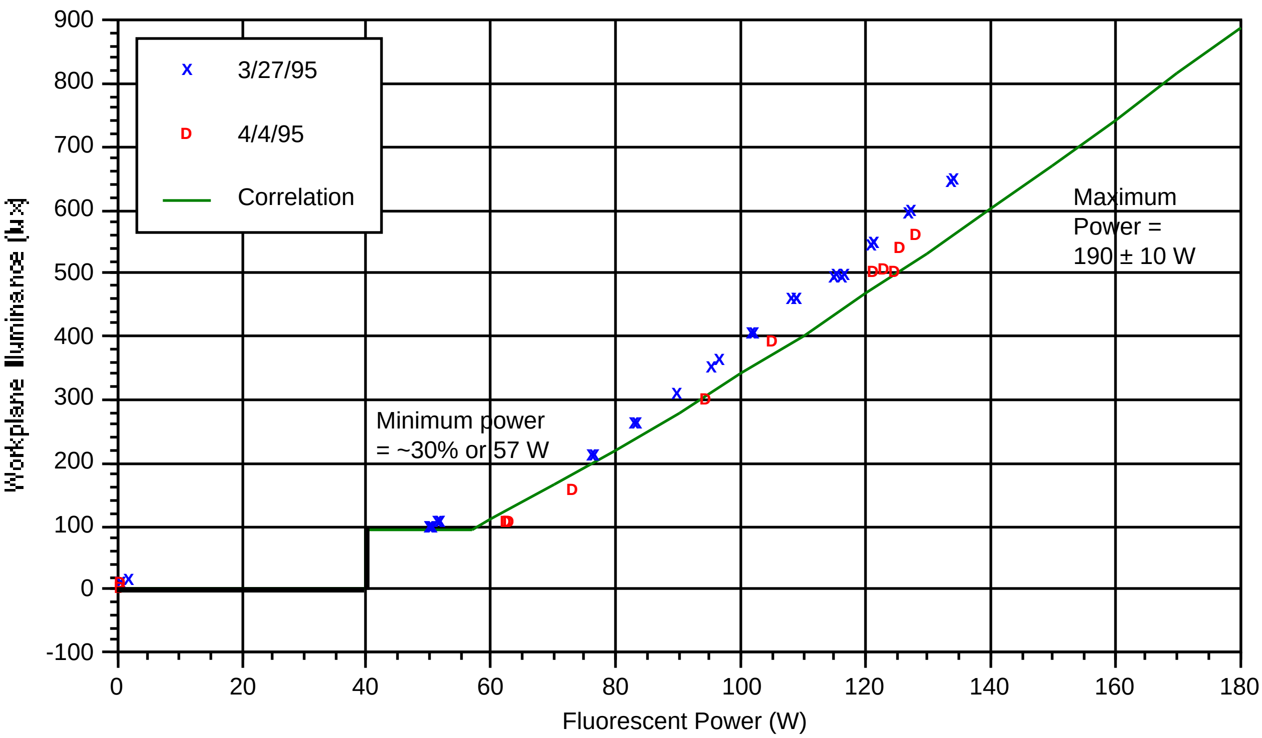

Figure 3. Electric lighting power consumption and the resultant average workplane illuminance (lux) as the lighting system is operated over its full dimming range, no daylight. Data points for two days are given, March 27, 1995 and April 4, 1995.

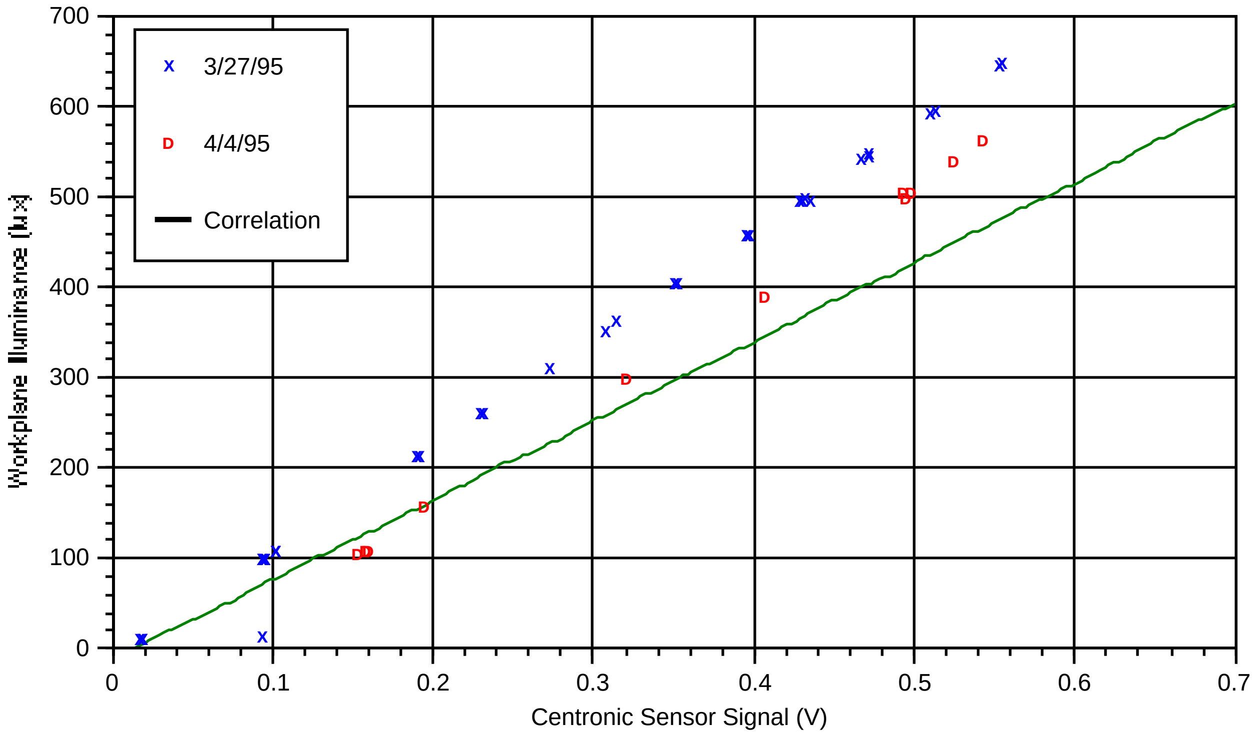

Figure 4. Centronics ceiling-mounted photosensor signal (V) and the resultant average workplane illuminance (lux) as the lighting system is operated over its full dimming range with no daylight. Data points for two days are given, March 27, 1995 and April 4, 1995.

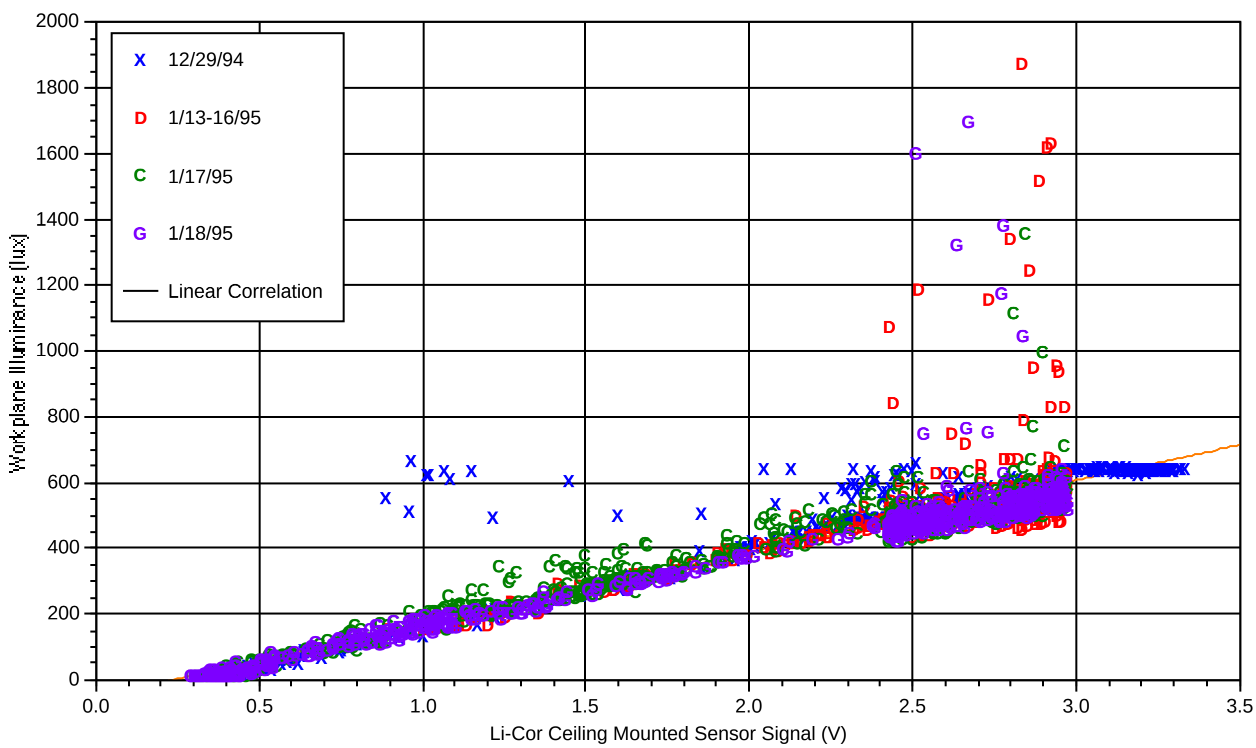

Figure 5. Li-Cor ceiling-mounted photosensor signal (V) and the resultant average workplane illuminance (lux) with an active blind system, daylight only. The correlation was based on December 29th data.

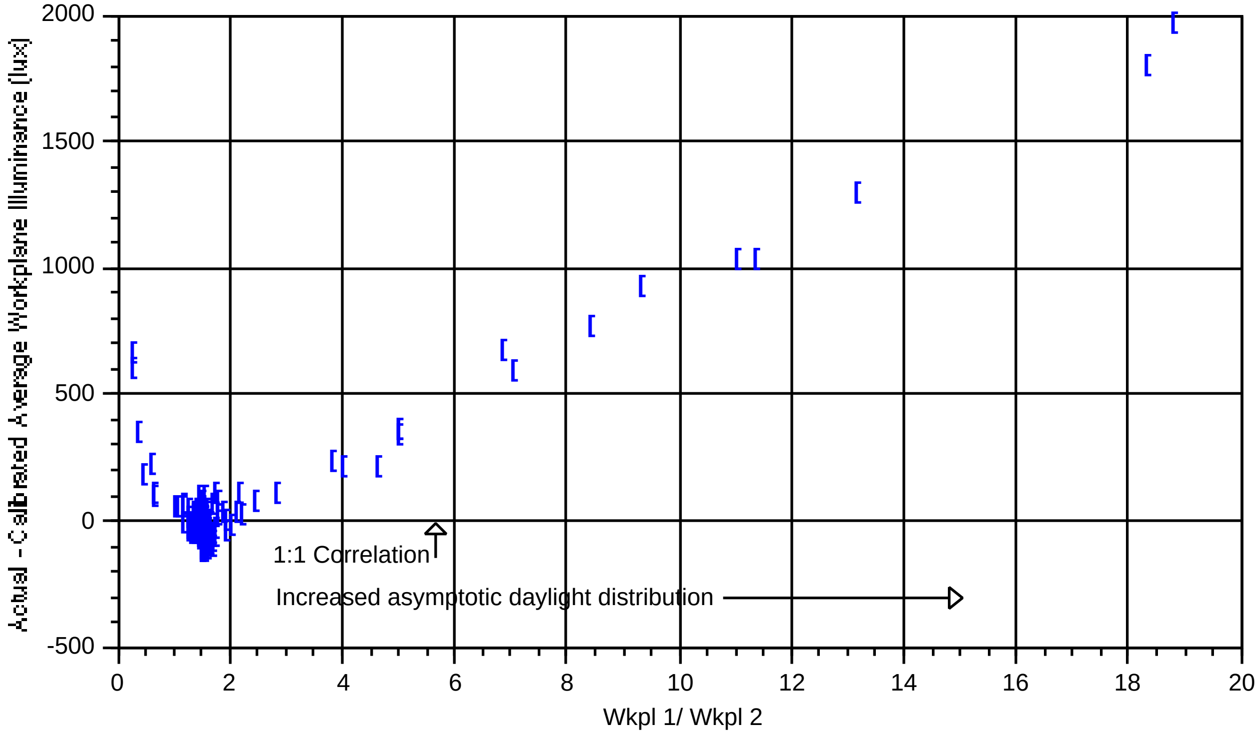

Figure 6. Ratio of workplane illuminance at 1.2 m from the window wall to the workplane illuminance at 2 m from the window, and the difference between actual average illuminance of four workplane sensors and the calibrated shielded Li-Cor workplane illuminance. The blinds were controlled to block direct sun and meet the design workplane illuminance level using the average workplane illuminance for control. Daylight only, no electric lighting, January 13-16, 1995, Southwest.

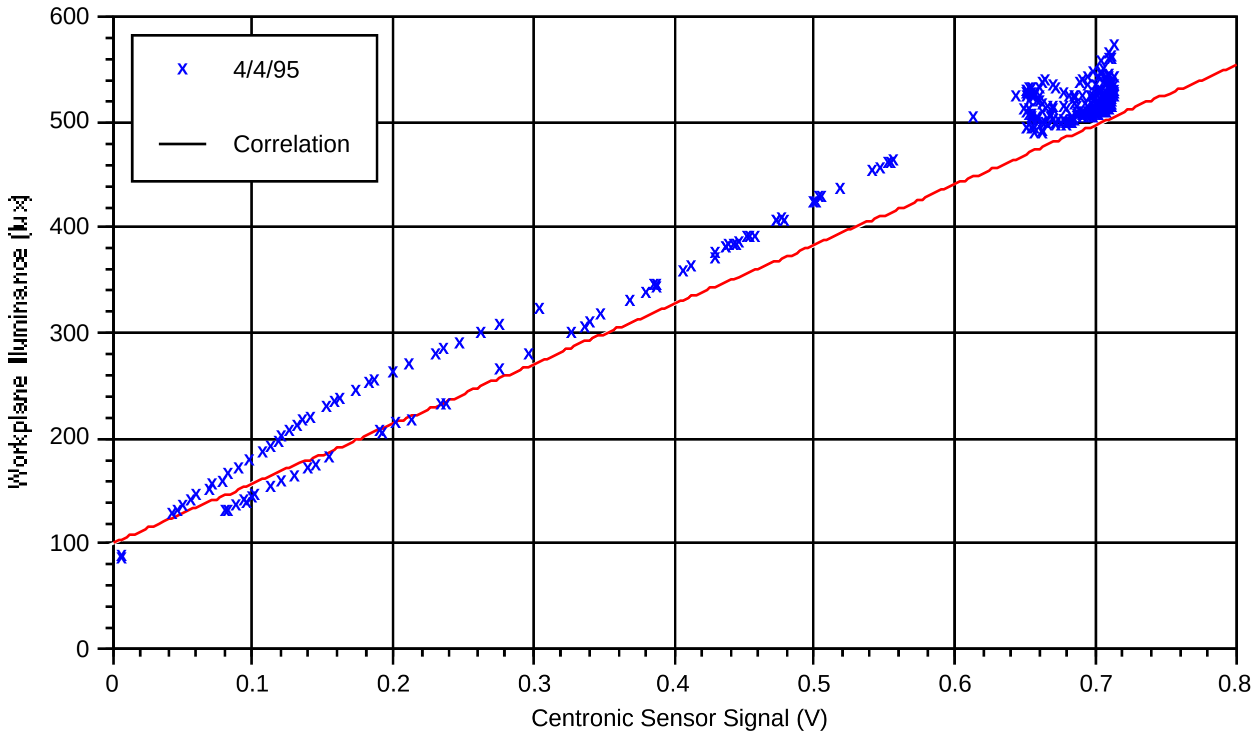

Figure 7. Centronics ceiling-mounted photosensor signal (V) and the resultant average workplane illuminance (lux) with an active blind, daylight only.

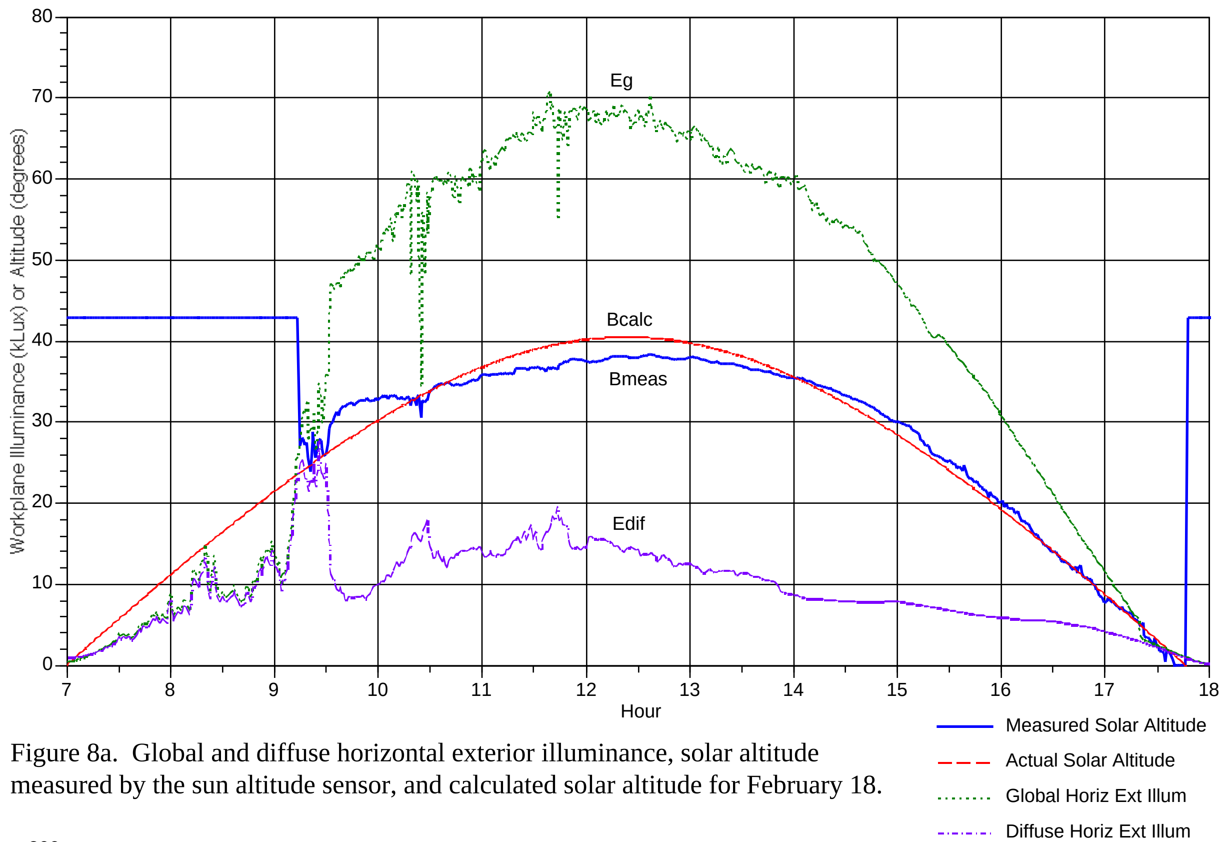

Figure 8a. Global and diffuse horizontal exterior illuminance, solar altitude measured by the sun altitude sensor, and calculated solar altitude for February 18.

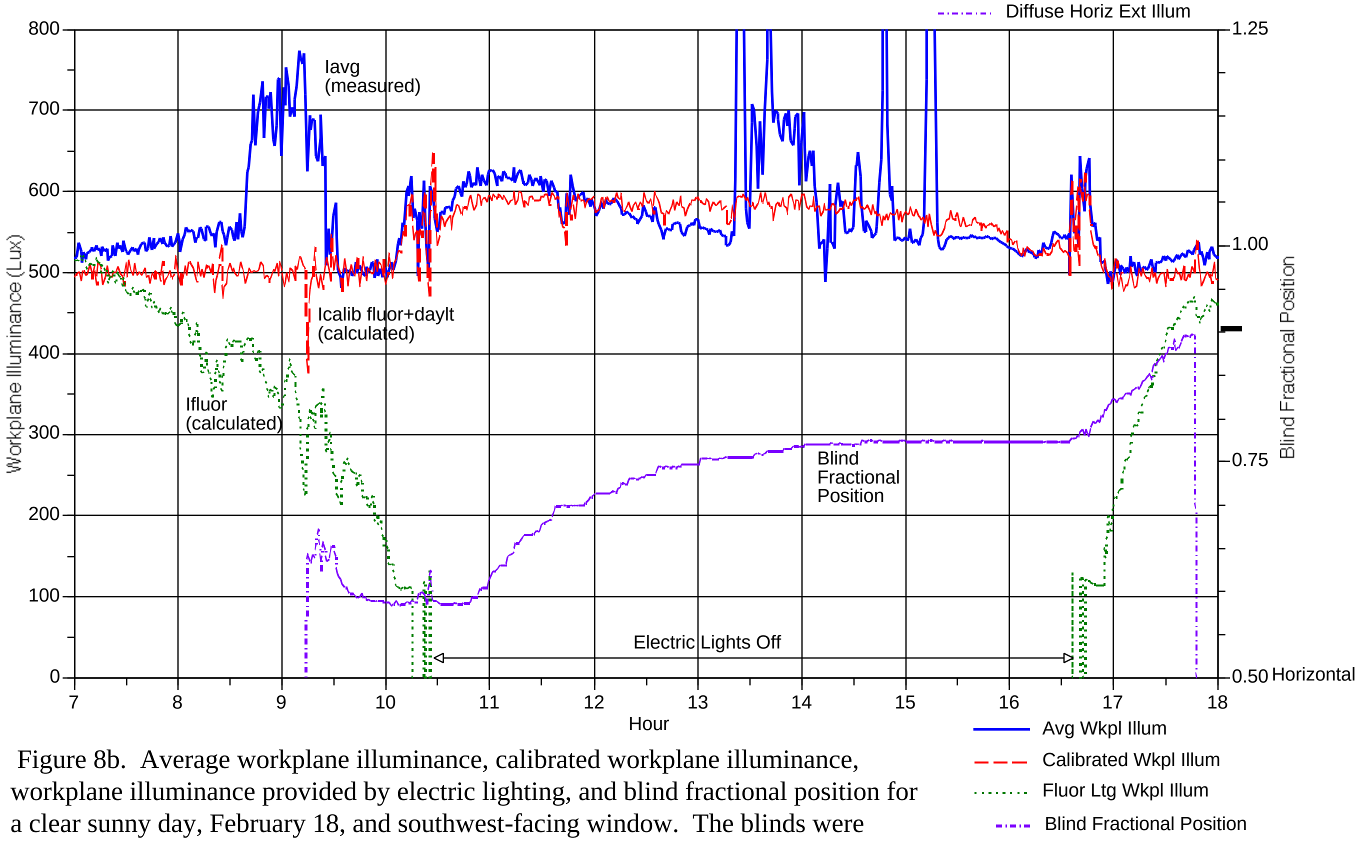

Figure 8b. Average workplane illuminance, calibrated workplane illuminance, workplane illuminance provided by electric lighting, and blind fractional position for a clear sunny day, February 18, and southwest-facing window. The blinds were controlled to block direct sun and meet the design workplane illuminance level using the shielded Li-Cor ceiling mounted photosensor for control. The electric lighting system was dimmed or shut off in response to the available daylight.

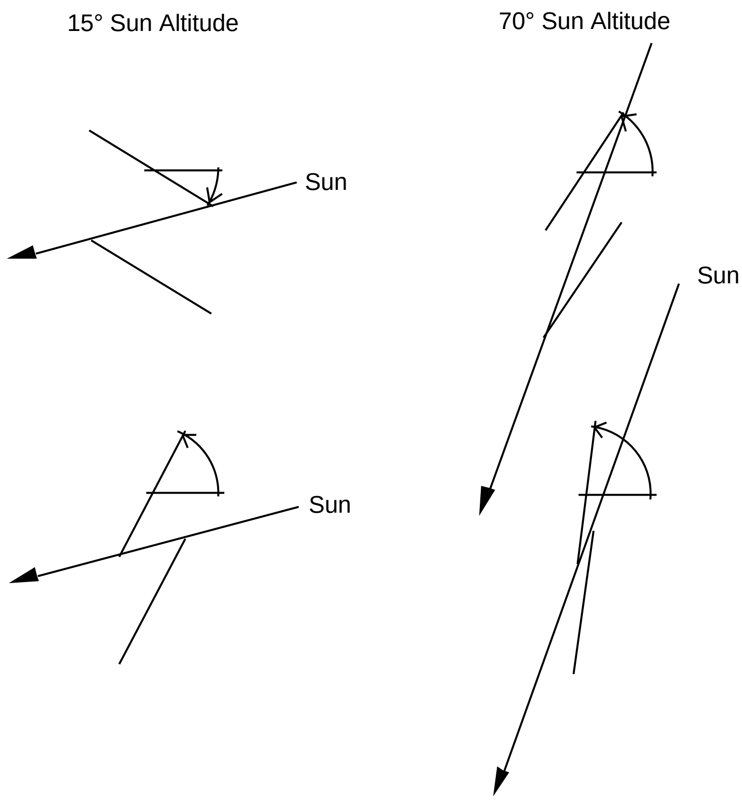

Figure 9. Cut-off blind angles that just block direct sun (grey areas are blind angles that block direct sun).

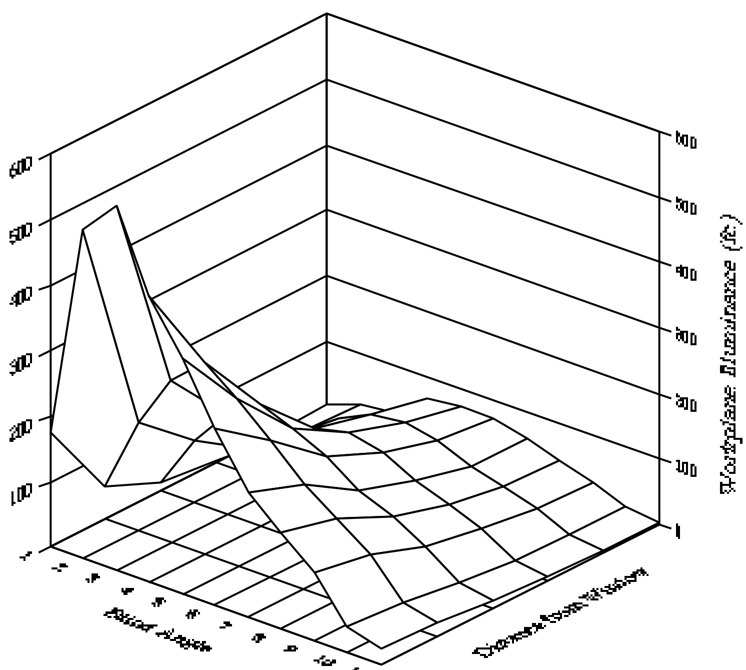

Figure 10. Predicted workplane illuminance (fc) as the blind angle is rotated 180˚ from an upwards (1) to downwards (11) slat angle as a function of distance from the window wall. Data are given for clear sky conditions on August 9 at 10:00 for a south-facing window (Lee and Selkowitz 1995). Predictions were based on bidirectional illuminance measurements within a physical model.

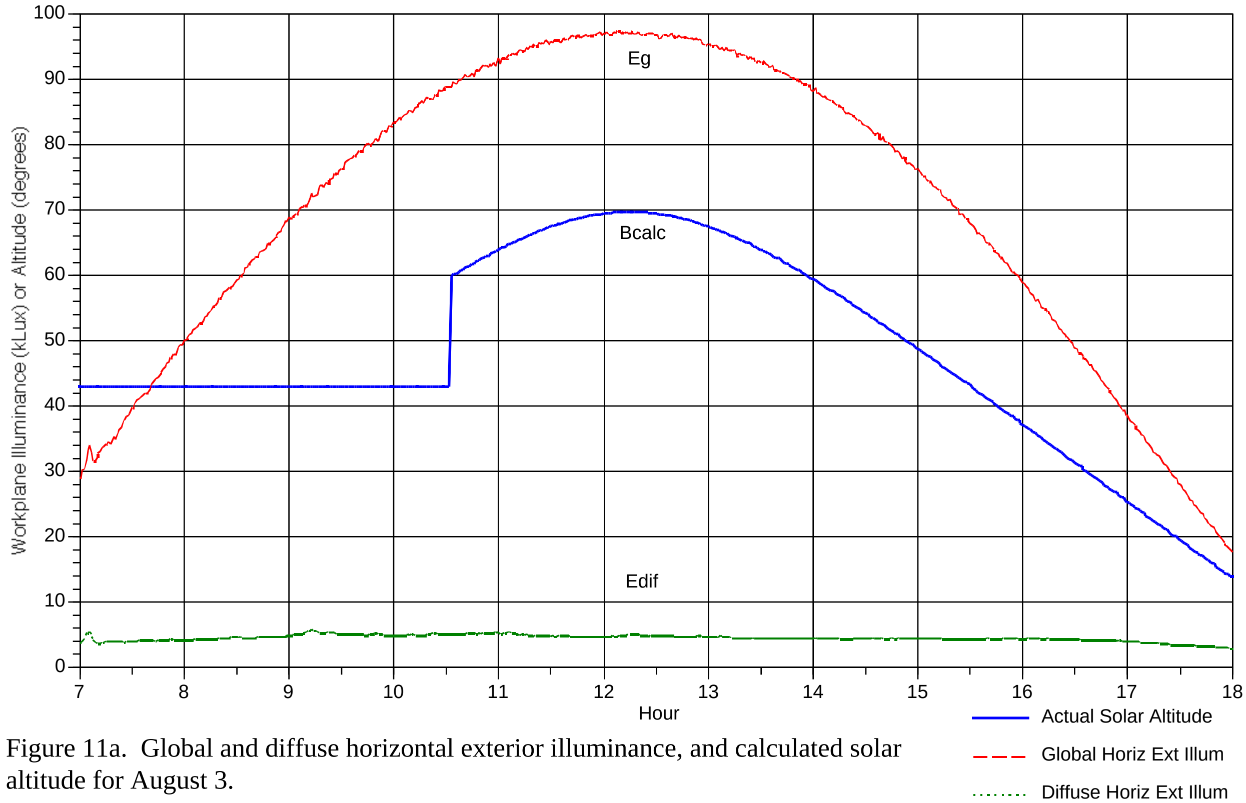

Figure 11a. Global and diffuse horizontal exterior illuminance, and calculated solar altitude for August 3.

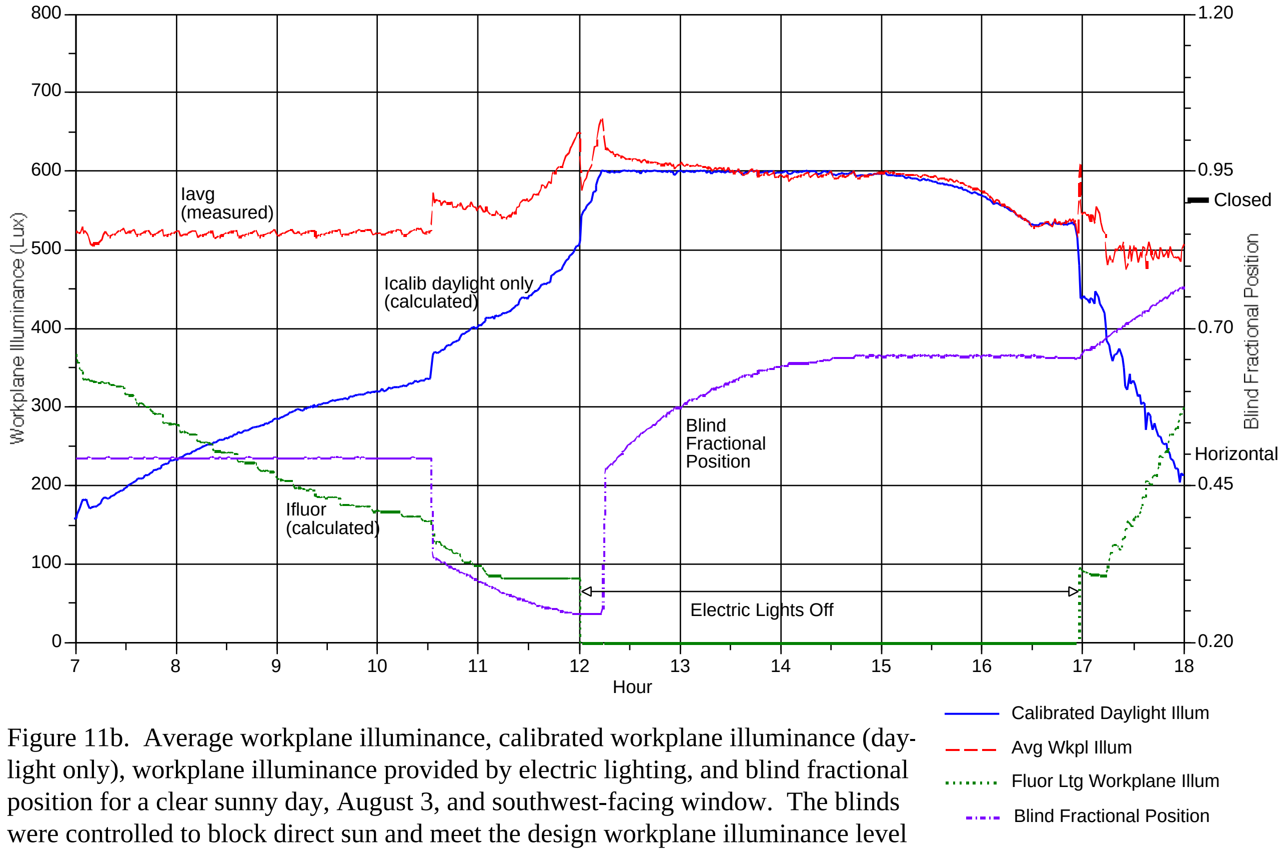

Figure 11b. Average workplane illuminance, calibrated workplane illuminance (daylight only), workplane illuminance provided by electric lighting, and blind fractional position for a clear sunny day, August 3, and southwest-facing window. The blinds were controlled to block direct sun and meet the design workplane illuminance level using the shielded Centronics ceiling mounted photosensor for control. The electric lighting system was dimmed or shut off in response to the available daylight.

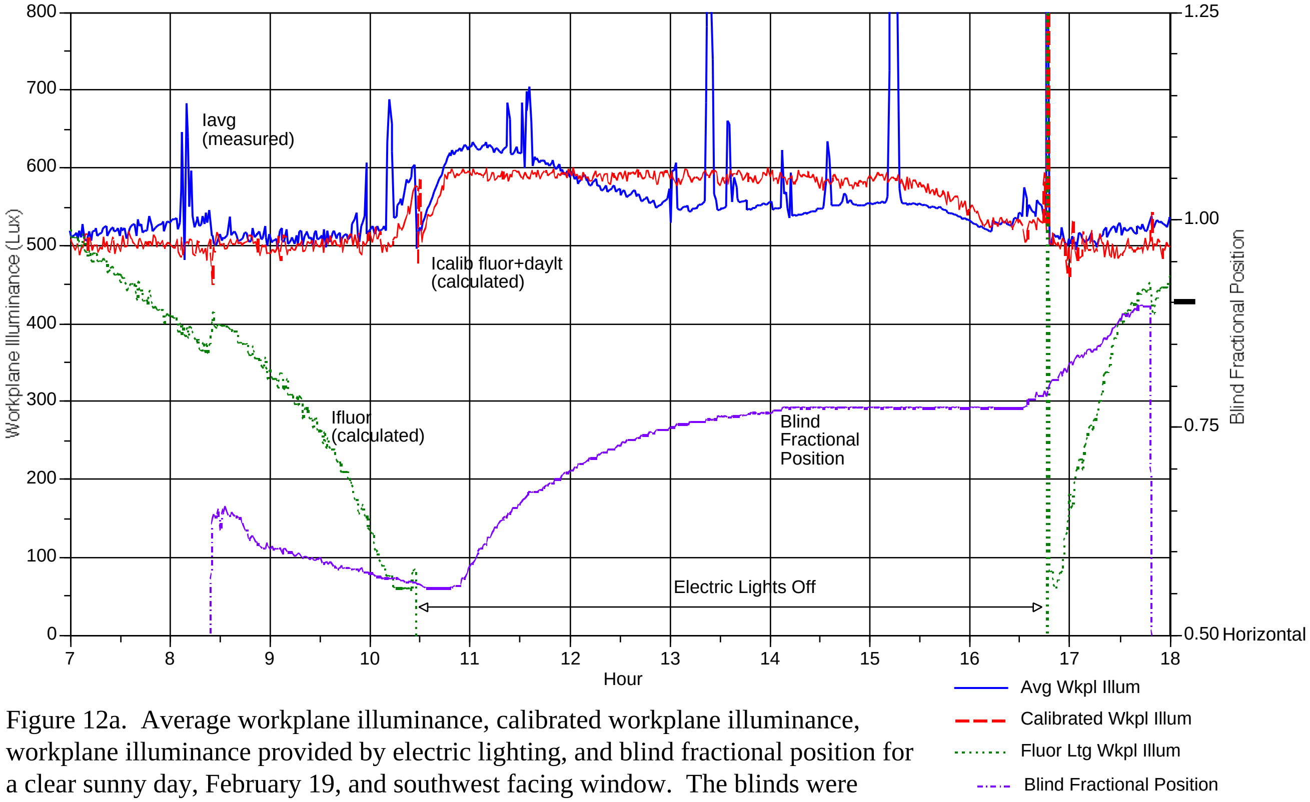

Figure 12a. Average workplane illuminance, calibrated workplane illuminance, workplane illuminance provided by electric lighting, and blind fractional position for a clear sunny day, February 19, and southwest facing window. The blinds were controlled to block direct sun and meet the design workplane illuminance level using the shielded Li-Cor ceiling mounted photosensor for control.

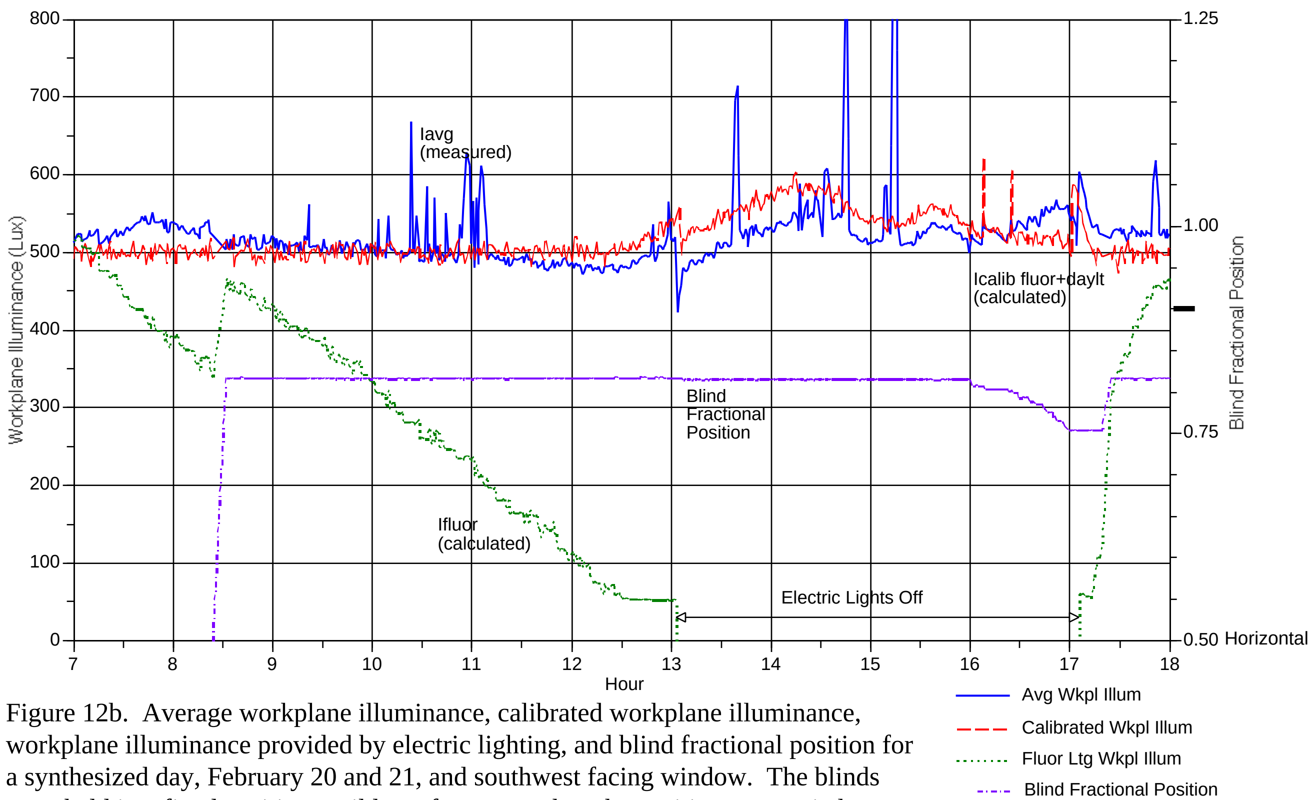

Figure 12b. Average workplane illuminance, calibrated workplane illuminance, workplane illuminance provided by electric lighting, and blind fractional position for a synthesized day, February 20 and 21, and southwest facing window. The blinds were held in a fixed position until late afternoon, when the position was varied to block direct sun. The shielded Li-Cor ceiling mounted photosensor was used to determine the calibrated workplane illuminance.

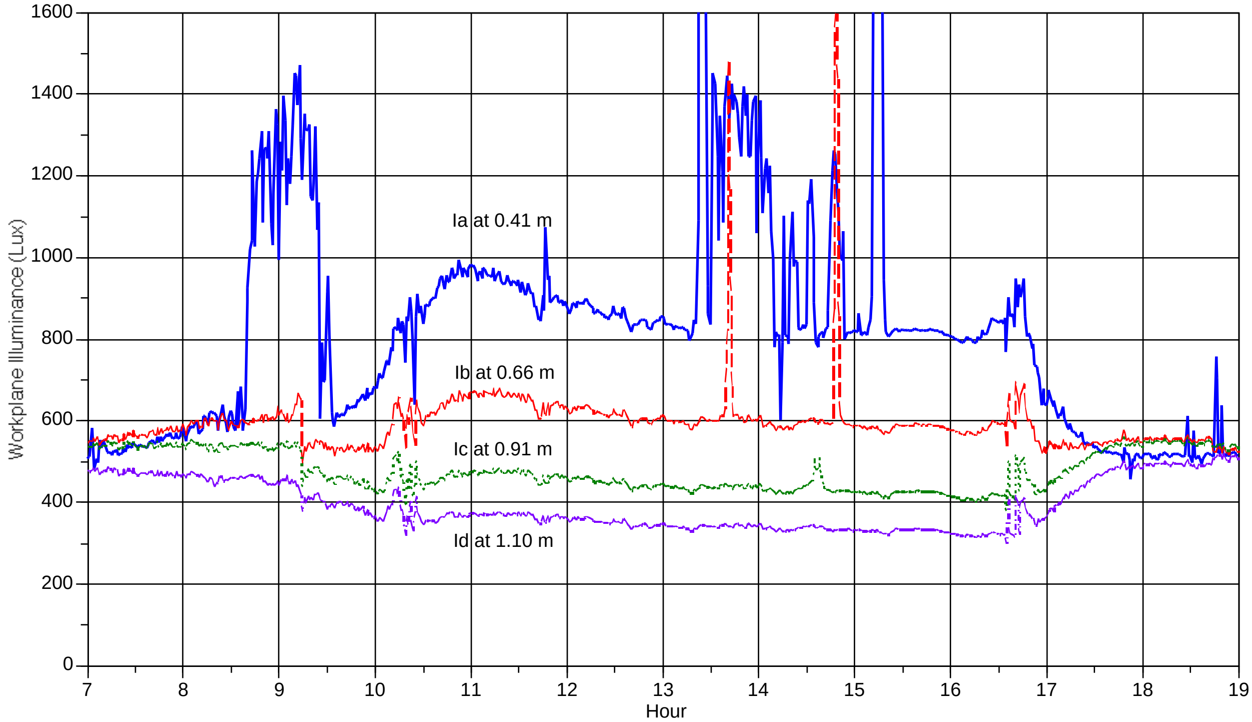

Figure 13. Workplane illuminance at 0.41, 0.66, 0.91, and 1.10 m from the southwest facing window wall for a clear sunny day, February 18. The blinds were controlled to block direct sun and meet the design workplane illuminance level using the shielded Li-Cor ceiling mounted photosensor for control. The electric lighting system was dimmed or shut off in response to the available daylight.

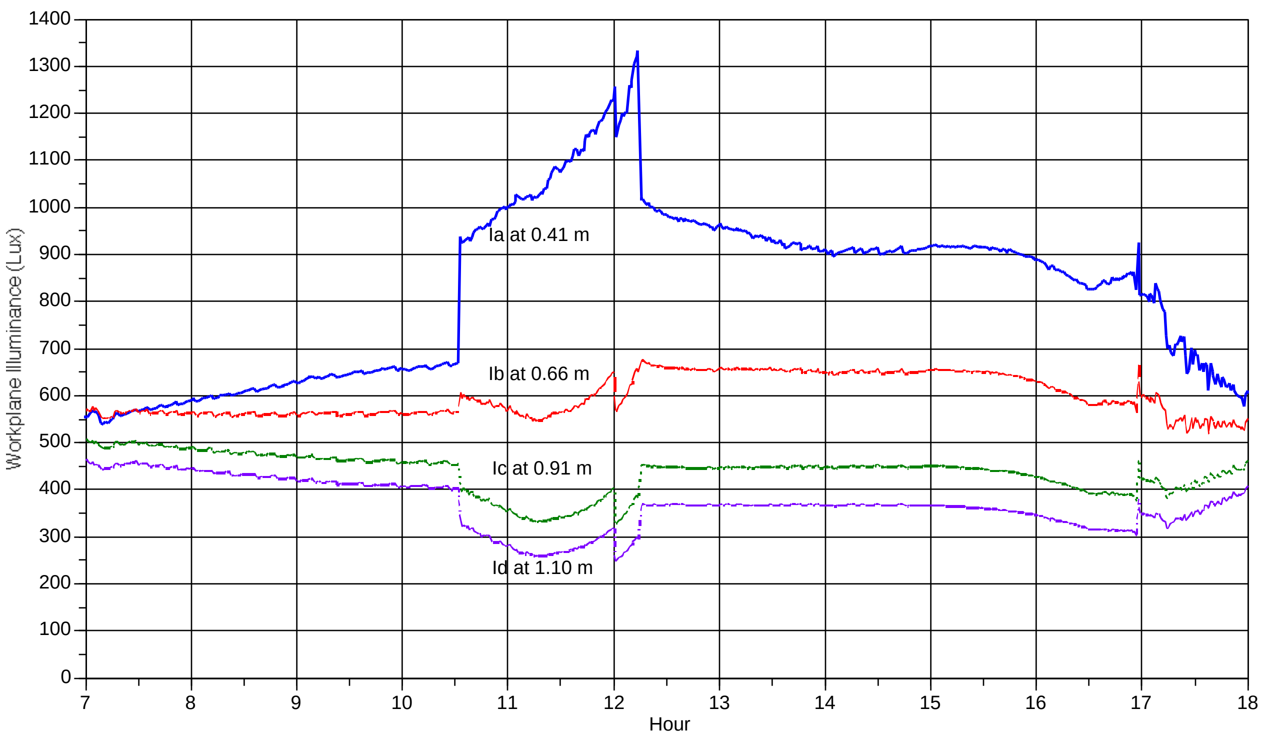

Figure 14. Workplane illuminance at 0.41, 0.66, 0.91, and 1.10 m from the southwest facing window wall for a clear sunny day, August 3. The blinds were controlled to block direct sun and meet the design workplane illuminance level using the shielded Centronics ceiling mounted photosensor for control. The electric lighting system was dimmed or shut off in response to the available daylight.